Post processing of Design Load Cases using Pdap

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Title: Post processing of Design Load Cases using Pdap

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Summary (max 2000 characters):

Pdap provides functions for post-processing and documentation of a set of hawc2 result files, e.g. a full design load case.

This report describes the input and its syntax, the mathematical foundation and the output in terms of statistic files and standard reports.

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Content

1. Summary

Pdap provides functions for post-processing and documentation of a set of hawc2 result files, e.g. a full design load case.

This report describes the input and its syntax, the mathematical foundation and the output in terms of statistic files and standard reports.

2. Introduction

Pdap, Python Data Analysis Program, is a program for post processing, analysis, visualization and presentation of data e.g. simulation results and measurements[1]. It provides provides a toolbox for post processing of a set of HAWC2 result files, e.g. a full full design load case, that includes:

- Extraction of sensor statistics
- Ultimate (extreme value) analysis
- Fatigue analysis

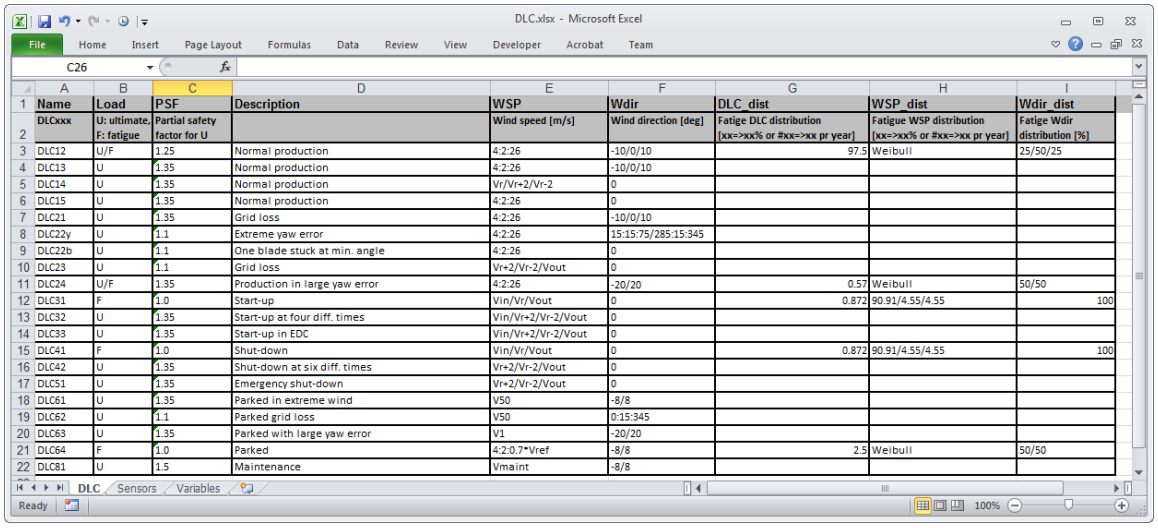
The Pdap post processing functions take as input an excel workbook and generates a statistic file for each sensor specified in the input workbook.
Based on these files, report elements or a full standard report can be generated.

3. Post processing input workbook

The post processing input workbook contains three sheets:

- DLC
- Sensors
- Variables

1. The DLC sheet



DLC.xlsx - Microsoft Excel

	Name	Load	PSF	Description	WSP	Wdir	DLC_dist	WSP_dist	Wdir_dist
2	DLCxxx	U: ultimate, F: fatigue	Partial safety factor for U		Wind speed [m/s]	Wind direction [deg]	Fatige DLC distribution [xx=>xx% or #xx=>xx pr year]	Fatigue WSP distribution [xx=>xx% or #xx=>xx pr year]	Fatige Wdir distribution [%]
3	DLC12	U/F	1.25	Normal production	4:2:26	-10/0/10	97.5	Weibull	25/50/25
4	DLC13	U	1.35	Normal production	4:2:26	-10/0/10			
5	DLC14	U	1.35	Normal production	Vr/Vr+2/Vr-2	0			
6	DLC15	U	1.35	Normal production	4:2:26	0			
7	DLC21	U	1.35	Grid loss	4:2:26	-10/0/10			
8	DLC22y	U	1.1	Extreme yaw error	4:2:26	15:15:75/285:15:345			
9	DLC22b	U	1.1	One blade stuck at min. angle	4:2:26	0			
10	DLC23	U	1.1	Grid loss	Vr+2/Vr-2/Vout	0			
11	DLC24	U/F	1.35	Production in large yaw error	4:2:26	-20/20	0.57	Weibull	50/50
12	DLC31	F	1.0	Start-up	Vin/Vr/Vout	0	0.872	90.91/4.55/4.55	100
13	DLC32	U	1.35	Start-up at four diff. times	Vin/Vr+2/Vr-2/Vout	0			
14	DLC33	U	1.35	Start-up in EDC	Vin/Vr+2/Vr-2/Vout	0			
15	DLC41	F	1.0	Shut-down	Vin/Vr/Vout	0	0.872	90.91/4.55/4.55	100
16	DLC42	U	1.35	Shut-down at six diff. times	Vr+2/Vr-2/Vout	0			
17	DLC51	U	1.35	Emergency shut-down	Vr+2/Vr-2/Vout	0			
18	DLC61	U	1.35	Parked in extreme wind	V50	-8/8			
19	DLC62	U	1.1	Parked grid loss	V50	0:15:345			
20	DLC63	U	1.35	Parked with large yaw error	V1	-20/20			
21	DLC64	F	1.0	Parked	4:2:0.7*Vref	-8/8	2.5	Weibull	50/50
22	DLC81	U	1.5	Maintenance	Vmaint	-8/8			

The dlc sheet contains information about the dlc groups

Column name (case insensitive)	Description	Examples
DLC	DLC group id	"11" "dlc22b"
Load	Include in ultimate (extreme) analyses and/or fatigue analysis.	"U": Include in ultimate analysis "F": Include in fatigue analysis "FU", "F/U", "F,U": include in both
PSF (optional)	Partial safety factor Safety factor for ultimate analysis related to this dlc group. Default is 1	"1": Max and min values is used directly "1.3": Max and min values are multiplied with 1.3 in ultimate analysis

WSP	Wind speed [m/s]	See xxx
DLC_dist	Fatigue dlc distribution.	See xxx_dist
WSP_dist	Fatigue wind speed distribution	See xxx_dist
xxx(optional)	Values distributed by xxx_dist	• "0" • "0:15:345": 0,15,30,…,345 • "0/350/10": 0,350,10 • "0,350,10": 0,350,10 Variables defined at the Variables sheet may be used, e.g. (x=10): • "x/x+2/x-2": 10,12,8
xxx_dist(optional)	Fatigue distribution of values in xxx [xx=>xx%], [#xx=>xx pr year]	• "80/10/10": 80% at first value, 10% at second and third values • "Weibull": see wind distribution • "Rayleigh": see wind distribution • "#1000/#50/#50": 1000 x first value pr. Year, 50 x second and third wsp pr year. (e.g. 1000 startups at Vin, 50 at Vr and 50 at Vout)

Wind distribution

For wind speeds specified in the "start:step:stop" format, e.g. "4:2:26", the "Weibull" or "Rayleigh" tags can be used in the wsp_dist column . Both tags yields the probability:

$$P(wsp) = e^{-\left(\frac{wsp-\frac{step}{2}}{\frac{2u}{\sqrt{\pi}}}\right)^2} - e^{-\left(\frac{wsp+\frac{step}{2}}{\frac{2u}{\sqrt{\pi}}}\right)^2}$$

Where:

u:	0.2Vref
Vref:	Reference wind speed of the wind class, defined at the Variables sheet
wsp:	each wind speed, e.g. 4,6,8,…,26
step:	The step between wind speeds, e.g. 2

Optional distributions

A number of optional values and corresponding distributions may be added. The order of these columns must be similar to the order of the tags in the filename.

Typical values and distributions are wind direction, wake direction etc.

For each xxx of these the sheet must have a “xxx”-column and a corresponding “xxx_dist”-column.

Probabilities

A group is a set of files that has the same values in the distribution tags, i.e. dlc, wsp and xxx, but different values in the tags that are not specified with a distribution in the sheet, e.g. seed etc.

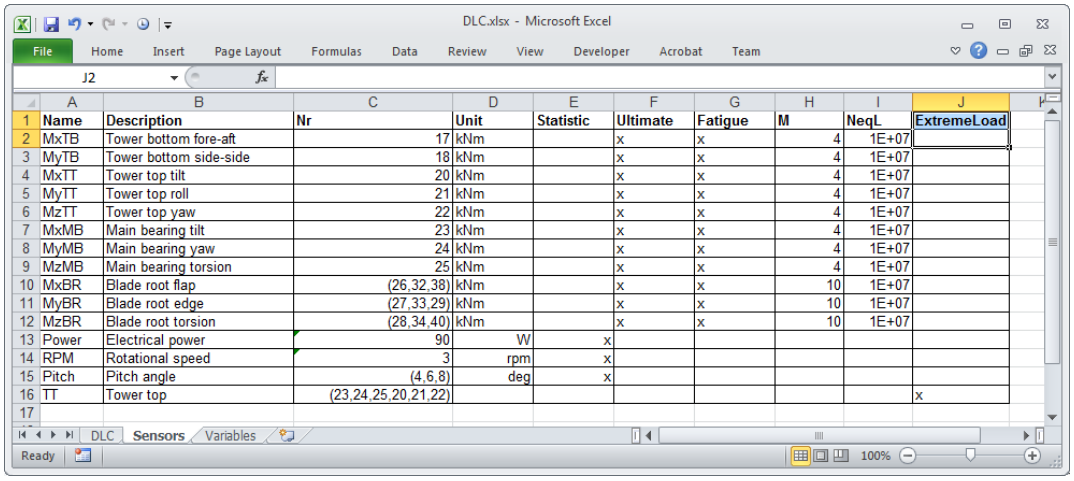
The probabilities of a group are the product of the xxx_dist-probabilites calculated from right to left until all distribution probabilities have been multiplied or a “#xxx” value is seen.

“#xxx”, e.g. “#1000” means 1000 of this simulation pr. year. I.e. the probability is the length of the simulation in seconds, len(file), divided by number of seconds pr. year, S_PR_YEAR. In this case all files in the same group must have the same length.

The probability of each file in the group is the probability of the group divided by the number of files in the group (Nfiles).

Dlc	Dlc_dist	Wsp	Wsp_dist	Wdir	Wdir_dist	Probability
31	2	4/12/25	90/5/5	350/0/10	25/50/25	dlc31_wsp04_wdir350: 0.25·0.9·0.02/Nfiles dlc31_wsp12_wdir000: 0.5·0.05·0.02/Nfiles
31	50	4/12/25	#1000/#50/#50	0	100	dlc31_wsp04_wdir000: 1·1000·len(file)/S_PR_YEAR/Nfiles Note that the dlc probability is ignored as it comes after ”#1000” read from right to left.

2. The Sensors sheet



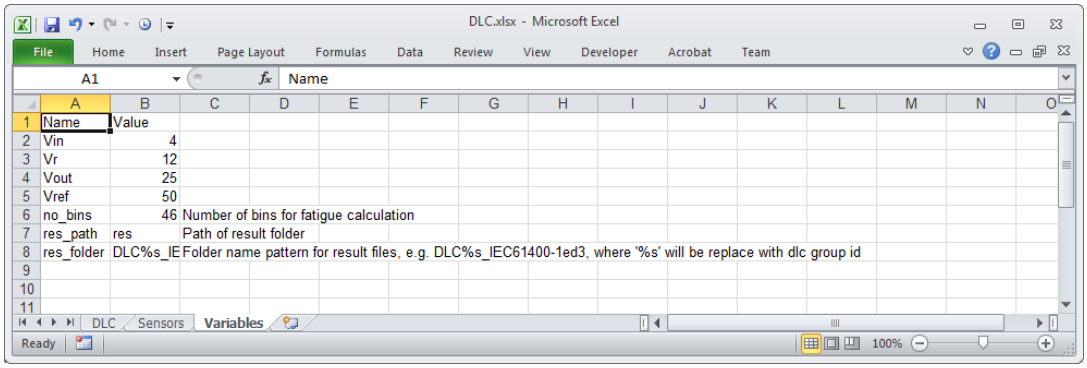
	A	B	C	D	E	F	G	H	I	J
1	Name	Description	Nr	Unit	Statistic	Ultimate	Fatigue	M	NeqL	ExtremeLoad
2	MxTB	Tower bottom fore-aft	17	kNm		x	x	4	1E+07	
3	MyTB	Tower bottom side-side	18	kNm		x	x	4	1E+07	
4	MxTT	Tower top tilt	20	kNm		x	x	4	1E+07	
5	MyTT	Tower top roll	21	kNm		x	x	4	1E+07	
6	MzTT	Tower top yaw	22	kNm		x	x	4	1E+07	
7	MxMB	Main bearing tilt	23	kNm		x	x	4	1E+07	
8	MyMB	Main bearing yaw	24	kNm		x	x	4	1E+07	
9	MzMB	Main bearing torsion	25	kNm		x	x	4	1E+07	
10	MxBR	Blade root flap	(26,32,38)	kNm		x	x	10	1E+07	
11	MyBR	Blade root edge	(27,33,29)	kNm		x	x	10	1E+07	
12	MzBR	Blade root torsion	(28,34,40)	kNm		x	x	10	1E+07	
13	Power	Electrical power	90	W	x					
14	RPM	Rotational speed	3	rpm	x					
15	Pitch	Pitch angle	(4,6,8)	deg	x					
16	TT	Tower top	(23,24,25,20,21,22)							x
17										

The Sensors sheet defines the desired sensors for the analysis

Column name (case insensitive)	Description	Examples
Name	Name of postprocessing sensor. The names must be unique. It is recommended to choose a short and descriptive name	"Power" "MxBR"
Nr	Sensor number in result files. Note that a certain sensor, e.g. Power, must have the same channel number, e.g. 90, in all results files. More sensors can be combined into a single postprocessing sensor, e.g. the blade root moments of the three blades	"90" "(26,32,38)"
Description (optional)	Description of the sensor	"Electrical power" "Blade root flap"
Unit (optional)	Unit of sensor	"W" "kNm"
Statistic (optional)	Defines which sensors to include in the statistic table and plots, see section 6. A nonempty field includes the sensor in the statistic table	"": Exclude "x": Include

	and plots, while an empty field excludes the sensor	
Ultimate (optional)	Defines which sensors to include in the extreme table and plots, see section 6. A nonempty field includes the sensor in the extreme table and plots, while an empty field excludes the sensor	“”: Exclude “x”: Include
Fatigue (optional)	Defines which sensors to include in the fatigue table and plots, see section 6. A nonempty field includes the sensor in the fatigue table and plots, while an empty field excludes the sensor	“”: Exclude “x”: Include
M (optional)	Wöhler slope coefficient for fatigue analysis	“4” “10”
NeqL (optional)	Lifetime equivalent load number for fatigue analysis	“1E+7” “1000000”
ExtremeLoad	Defines which sensors to include in the extreme load table, see section 6. A nonempty field includes the sensor in the extreme load table, while an empty field excludes the sensor. The corresponding “Nr”-field must contain 6 numbers specifying the Fx, Fy, Fz, Mx, My, Mz sensor numbers	“”: Exclude “x”: Include

3. The Variables sheet



The Variables sheet defines variables required for the post processing as well as custom variables used in the DLC sheet.

The first column specifies the name of the variables and the second column their values.

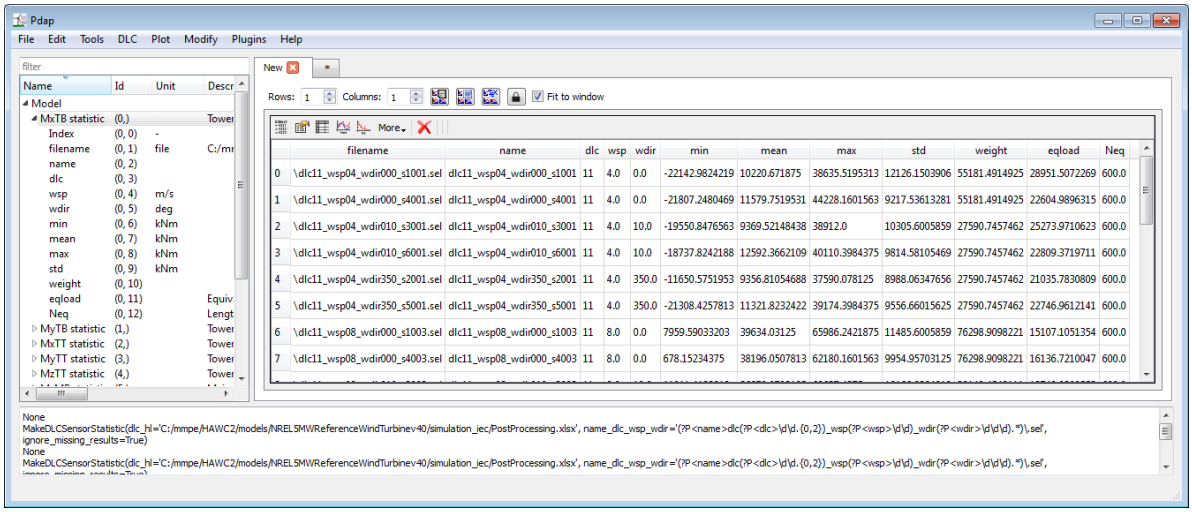
Variable (case sensitive)	Description	Examples
res_path	Path to the folder that contains the result files or subfolders with result files	“res” “iec_res”
no_bins	Number of bins for fatigue analysis	“46”
m_list	List of Wöhler slope coefficients for the fatigue analysis. A eqloadxx sensor will be added to the statistic files for each value in the list	“3,4,6,8,10,12” (default)
res_folder (optional)	Name pattern for result subfolders. If “%s” in the res_folder value, then “%s” will be replaced with the dlc group id	“”: No sub folder (default) “DLC%s_IEC61400-1ed3”
Vref	Reference wind speed of the wind class	“50”
X	Custom variables used at the DLC sheet, e.g. ‘Vin’	“10”

4. Statistic files

4. Generating statistic files

From Pdap statistic files are generated via the “Make sensor statistic files” (menu – DLC – Make sensor statistic files).

This function opens a dialog requesting the DLC input file (workbook) and generate a statistic file for each post processing sensor, see figure below.



The statistic files are saved in the folder: <res_path>/stat/<sensor name>.h5

The files can be loaded, viewed and plot via Pdap.

5. Naming convention

When generating the statistic files via the menu, the default parameters are used (use scripting to apply with custom parameters). This means that the result files must obey to the following standard naming convention to be found by the fatigue analysis function:

Filename: dlcxxx_wsp00_wdir000*.sel

dlc: group id, e.g.: 11, 22b
wsp: wind speed [m/s]
wdir: wind direction % 360 [deg]

Examples of valid filenames:
dlc11_wsp04_wdir350_s1001.sel
dlc22b_wsp04_wdir000.sel

6. Contents of statistic files

The statistic files contain the following attributes

Name	Description
filename	Filename of result file. Combined with describtion, the full path is obtain. Special “file” unit, see select dataset plot
name	Case id
Dlc	Dlc group id
wsp	Wind speed
wdir	Wind direction
min	Minimum value
mean	Mean value*
max	Maximum value
std	Standard deviation**
weight	Weight of case, see weight calculation example
eqload	Short term equivalent load, i.e. range of 1Hz signal that results in equivalent load
Neq	Equivalent load number, i.e. number of 1Hz cycles (duration of simulation in cycles)

* For sensors measured in degrees or radians (lowercase(unit) = “deg” or “rad”) the mean is calculated by:

$$mean(x) = atan2(mean(\sin(x)), mean(\cos(x)))$$

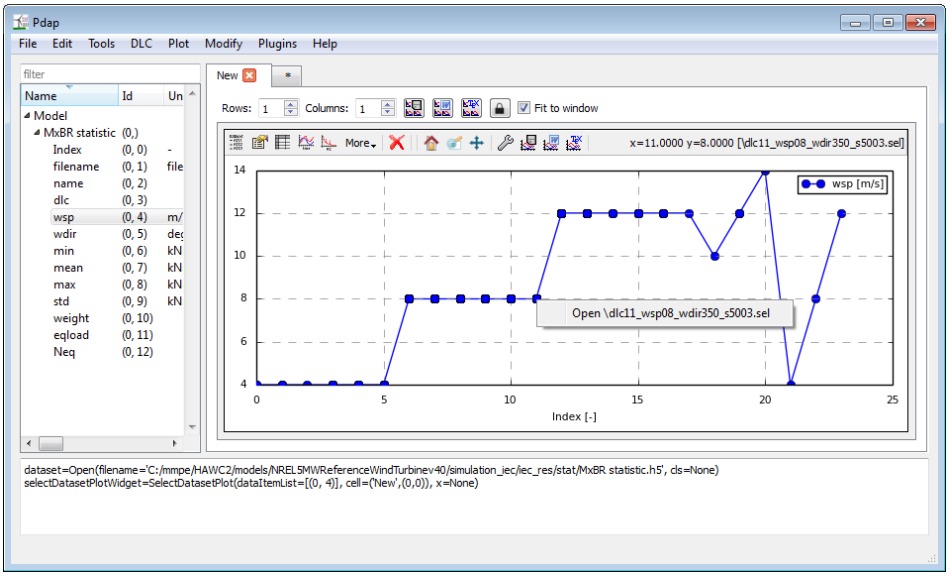
** For sensors measured in degrees or radians (lowercase(unit) = “deg” or “rad”) the std is calculated by:

$$std(x) = \sqrt{1 - (mean(\sin(x))^2 + mean(\cos(x))^2)}$$

7. Select dataset plot

The special “file” unit of the filename attribute enables the “Select dataset plot” option (right click on sensor – Plot – Select dataset plot).

In this plot the file name is seen next to the cursor position in the right side of the cell toolbar and the dataset (result file) represented by a dot, can be opened by right-clicking the dot, see figure below.



5. Fatigue analysis

8. Short term equivalent load, stel

$$stel = \left(\frac{(\sum n_i S_i^m)}{Neq}\right)^{1/m}$$

Where

n_i: Number of cycles with range S_i
m: Wöhler slope
Neq: Length of simulation in seconds

9. Life time equivalent load

$$Life\ time\ equivalent\ load = \left(\frac{(\sum stel^m \cdot Neq\ \cdot weight)}{NeqL}\right)^{1/m}$$

Where

$stel$: Short term equivalent load, see above
m: Wöhler slope
Neq: Length of simulation in seconds
$weight$: See below
$NeqL$: Lifetime equivalent load number as defined in the "Sensor" sheet

Weight calculation

The weight specifies how many times a result file should be included in 20 years of operation.

Example 1: dlc11_wsp04_wdir000_s1001

First calculate the probability of the case:

$$P(case) = P(dlc11) \cdot P(wsp) \cdot P(wdir) = 0.975 \cdot 0.213 \cdot 0.5 = 0.105$$

As

$$P(wsp) = e^{-\left(\frac{wsp+\frac{step}{2}}{\frac{2u}{\sqrt{\pi}}}\right)^2} - e^{-\left(\frac{wsp-\frac{step}{2}}{\frac{2u}{\sqrt{\pi}}}\right)^2} = e^{-\left(\frac{4-\frac{4}{2}}{\frac{2\cdot 0.2\cdot 10}{\sqrt{\pi}}}\right)^2} - e^{-\left(\frac{4+\frac{4}{2}}{\frac{2\cdot 0.2\cdot 10}{\sqrt{\pi}}}\right)^2}$$
$$= 0.967 - 0.754 = .215$$

Then the number of hours in 20 years of this case

$$Hours(case) = P(case) \cdot \frac{hours}{20year} = 0.105 \cdot 20 \cdot 365 \cdot 24 = 18194$$

And finally the weight of each file is calculated based on the length of the file (=600s) and the number of files for this case (=2), i.e. same dlc, wsp and wdir, but different seed.

$$Weight(case) = hours \cdot \frac{3600sec/hour}{len(case) \cdot files\ pr\ case} = 18194 \cdot \frac{3600}{600 \cdot 2} = 55181$$

6. Report elements

From the generated statistic files some standard report elements, see sections below, can be generated.

The report elements can be generated separately (menu – DLC – Report element – xxx) or all together (menu – DLC – Full standard report).

Sensor table

The sensor table gives an overview of the postprocessing sensors, including names, units and descriptions

Nr	Name	Unit	Description
17	MxTB	kNm	Tower bottom fore-aft
(26,32,38)	MxBR	kNm	Blade root flap
90	Power	W	Electrical power
(23,24,25,20,21,22)	TT		Tower top

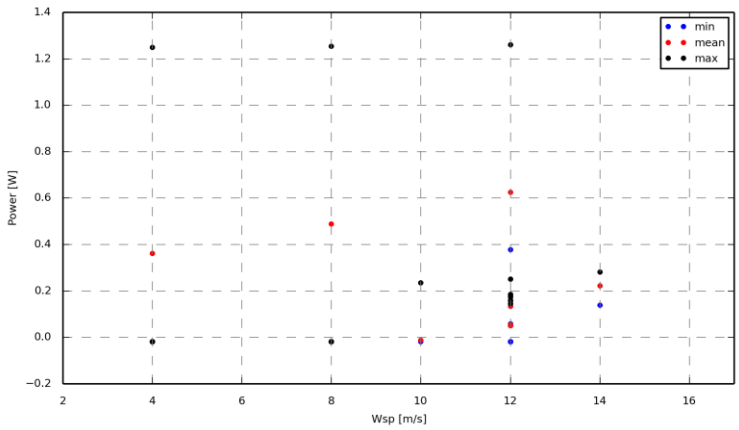
10. Statistic table

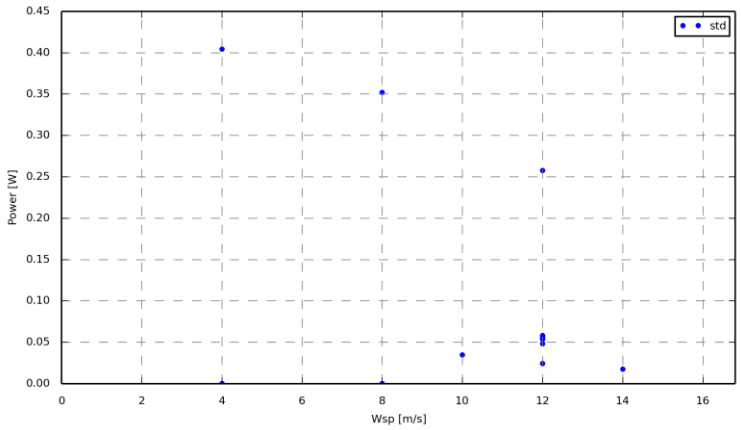
The statistic table shows the minimum, mean and maximum values

Name	Min	Mean	Max
Power	-1.92E-02	7.91E-02	1.26E+00

Statistic plots

The statistic plots show the min, mean, max and std(separate plot) of each result file as function of wind speed





Extreme table

The extreme table shows the minimum and maximum values including partial safety factor found in any ultimate analysis files as well as the id of the file where the value is found.

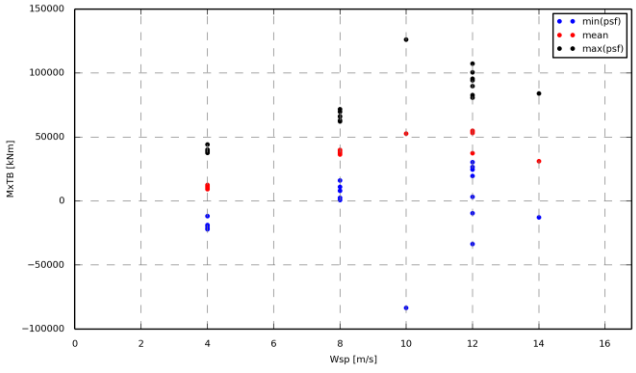
Ultimate analysis files are the result files of the dlc groups that have a “U” in the “Load” column of the DLC sheet.

Name	Min incl. psf	Max incl. psf	DLC min	DLC max
MxTB	-8.36E+04	1.26E+05	14_wsp10_wdir000	14_wsp10_wdir000
MxBR	-2.07E+04	1.56E+04	14_wsp10_wdir000	14_wsp10_wdir000

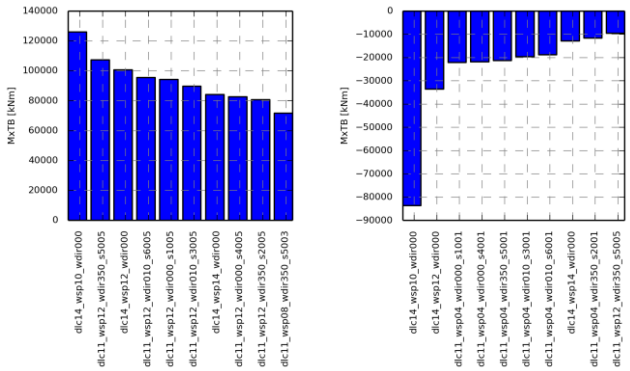
Extreme plots

The extreme plots consist of different plots showing extreme values including partial safety factor of the ultimate analysis files.

The first shows the min, mean and max values of all result files as function of wind speed.

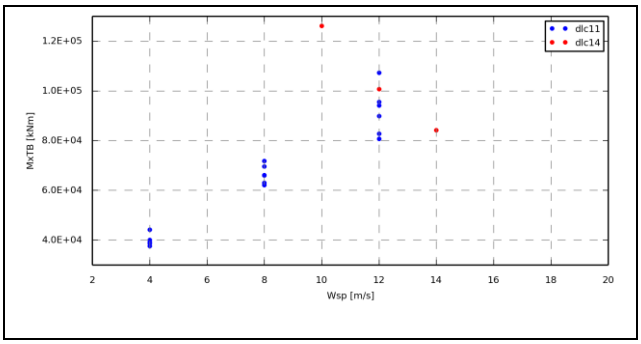


Then two bar charts shows the 10 most extreme values and the id of the corresponding result files



Maximum values **Minimum values**

Finally two pages shows the maximum and minimum values respectively. In this case the dlc main group, i.e. 1x, 2x, … are shown in individual plot and dlc sub groups, e.g. 11, 14, … are marked with different colors.



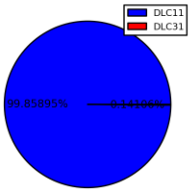
Fatigue table

The fatigue table shows the Life time equivalent load and the corresponding m and Neq values.

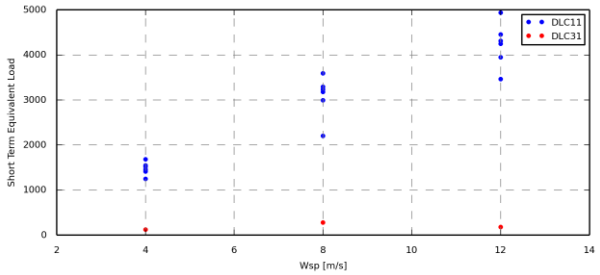
Sensor	Life time equivalent load	m	neq
MxTB	5.488E+04	4	1E+07
MxBR	1.341E+04	10	1E+07

Fatige plot

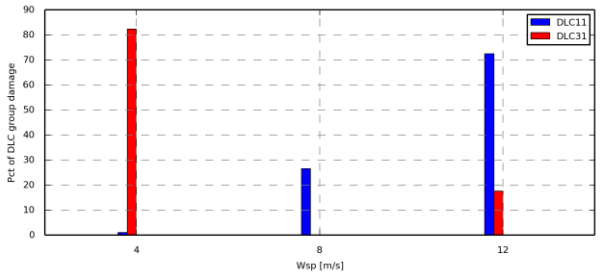
The fatigue plot consist of three different plots. The first is a pie chart showing the amount of damage in percent caused by each dlc group included in the fatigue analysis, i.e. groups that have a “F” in the “Load” cell in the DLC sheet.



The next plot shows the short term equivalent load of each result file as function of wind speed. DLC groups are separated by colors.



The last plot shows the amount of damage caused by each dlc group for each wind speed.



Extreme load table

The extreme load table shows the minimum and maximum loads (forces and moments) as well as the id of the result file in which the load occurs. In addition the values of the other sensors of the observation where the extreme occurs are listed.

		Loadcase	SF	Fx	Fy	Fz	Fres	Mx	My	Mz	Mres
Fx	Max	dlc11_wsp04_wdir350_s5001	1	+1.4E+02	+4.3E+01	+3.5E+03	+1.5E+02	+8.8E+02	+8.1E+02	-4.4E+02	+1.2E+03
	Min	dlc14_wsp12_wdir000	1	-2.0E+02	-2.9E+02	+3.4E+03	+3.5E+02	+5.8E+03	+4.5E+03	-5.3E+03	+7.4E+03
Fy	Max	dlc11_wsp12_wdir350_s5005	1	+2.8E+00	+1.2E+03	+3.5E+03	+1.2E+03	+7.0E+02	+4.0E+03	+1.5E+01	+4.1E+03
	Min	dlc14_wsp10_wdir000	1	-1.7E+02	-7.2E+02	+3.4E+03	+7.4E+02	+6.3E+03	+4.0E+03	-7.4E+03	+7.4E+03
Fz	Max	dlc11_wsp12_wdir350_s5005	1	+1.0E+01	+6.8E+02	+3.6E+03	+6.8E+02	+4.2E+03	+4.5E+03	-6.4E+03	+6.2E+03
	Min	dlc14_wsp10_wdir000	1	-1.2E+02	-6.4E+02	+3.4E+03	+6.5E+02	+8.0E+03	+3.9E+03	-6.9E+03	+8.9E+03
Fres	Max	dlc11_wsp12_wdir350_s5005	1	+2.8E+00	+1.2E+03	+3.5E+03	+1.2E+03	+7.0E+02	+4.0E+03	+1.5E+01	+4.1E+03
	Min	dlc31_wsp04_wdir000	1	-7.4E-02	-1.2E-02	+3.4E+03	+7.5E-02	-1.3E+03	-1.3E+00	+1.5E+01	+1.3E+03
Mx	Max	dlc14_wsp10_wdir000	1	-6.4E+01	-4.3E+02	+3.4E+03	+4.3E+02	+8.6E+03	+4.1E+03	-4.7E+03	+9.5E+03
	Min	dlc14_wsp10_wdir000	1	-1.3E+02	+4.3E+02	+3.4E+03	+4.4E+02	-1.1E+04	+3.2E+03	+4.2E+03	+1.2E+04
My	Max	dlc14_wsp14_wdir000	1	-5.8E+01	+2.3E+02	+3.5E+03	+2.4E+02	+4.9E+03	+5.0E+03	-8.1E+03	+7.0E+03
	Min	dlc11_wsp04_wdir000_s1001	1	-4.6E+01	-1.3E+02	+3.4E+03	+1.3E+02	-8.3E+02	-1.0E+02	+1.8E+03	+8.4E+02
Mz	Max	dlc11_wsp12_wdir010_s3005	1	-4.9E+01	+6.6E+02	+3.5E+03	+6.6E+02	+1.8E+03	+2.8E+03	+9.5E+03	+3.3E+03
	Min	dlc14_wsp14_wdir000	1	-1.8E+02	+4.0E+01	+3.5E+03	+1.8E+02	+6.5E+03	+4.8E+03	-8.7E+03	+8.1E+03
Mres	Max	dlc14_wsp10_wdir000	1	-1.3E+02	+4.3E+02	+3.4E+03	+4.5E+02	-1.1E+04	+3.3E+03	+4.0E+03	+1.2E+04
	Min	dlc11_wsp04_wdir350_s2001	1	-2.2E+01	+8.5E+01	+3.4E+03	+8.8E+01	-1.8E+01	+1.8E+00	+1.4E+03	+1.8E+01

References

[1] M. M. Pedersen and T. J. Larsen, *Pdap Manual Wind Energy E Report 2014*, no. December. 2014.

DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

We have more than 240 staff members of which approximately 60 are PhD students. Research is conducted within nine research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.

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